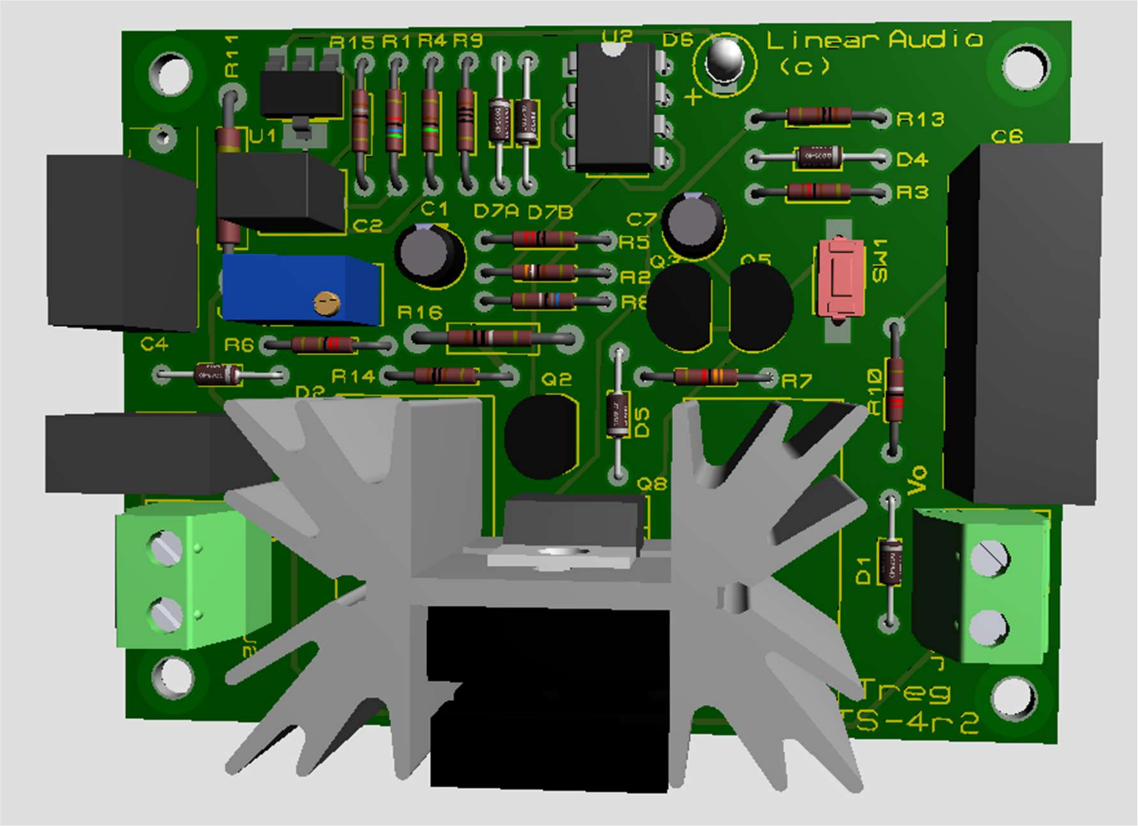
T-reg –

A high-voltage, low noise, fully protected regulator

Jan Didden, Linear Audio



Warning!

This project involves very high voltages, potentially up to 500V and these are voltage that can seriously harm and even kill you! If you are inexperienced with such circuits, or feel uncomfortable with such high voltages, do not attempt this project, or ask experienced help. There is only one party responsible for your safety – you. Not me, not diyaudio, not anybody else. Be sensible if you have any doubt as to your ability to complete this project in a safe way. There are many other projects for you to cut your teeth on without killing you. You have been warned!

Introduction

T-reg is a high voltage regulator aimed at tube-level high voltage amplifiers. The circuit that can be built up on the PCB offered at the diyaudio store and can provide an output voltage between 0 (probably less useful) up to 500V, at currents up to 400mA. T-reg accepts input voltages from a transformer/rectifier/capacitor supply up to a maximum of 500V.

Performance is very good, with less than 10uV broadband noise, and less than 20mΩ output impedance[1]. That means a clean supply that doesn't sag with varying load. For lower current requirements it has an on-board heatsink, but the pass device can also be mounted on a larger heatsink or on the chassis.

Both the output voltage and the current limit can be set by a single resistor. If the current limit is exceeded for more than a fraction of a second, the regulator shuts down to protect both the load and itself. Depending on the input-output voltage difference and current draw, the heatsink can be either on or off the PCB. Fig 1 gives an impression of a T-reg with on-PCB heatsink. PCB size is approximately 3.1 x 2.3 inch (78 x 58 mm).

Fig 1 shows the complete circuit. To help you to quickly get up to speed on the circuit, we will look at the various functional sections in turn. It may be useful to have a printout of the schematic for reference.

The bare regulator. The primary, unregulated dirty supply comes in at the bottom left at connector J2 – Vraw, and the clean, stable, low noise regulated voltage exits to your circuit-to-be-powered at the bottom right from J3 – Vout. In between is the main regulating device Q1, a high power MOSFET. There are also some resistors in the line, R6 and R8, which will be discussed later under Current Limit, but let’s for the moment pretend they are not there. The task of Q1 is to let current through from input to output depending on the current draw. It will need to open just enough to support that current, without changing Vout even a bit. Q1 needs help, and gets it from IC opamp U2, an AD8031. U2 compares Vout to a reference voltage, and when there is a deviation, opens or closes Q1 as required to maintain Vout to the set value. How does U2 do that?

---

[1] 20mΩ is already overkill. Once you add the resistance of some kind of connector terminal pin, wiring to the circuit to be powered and a couple of solder joints, you will have added much more than that.

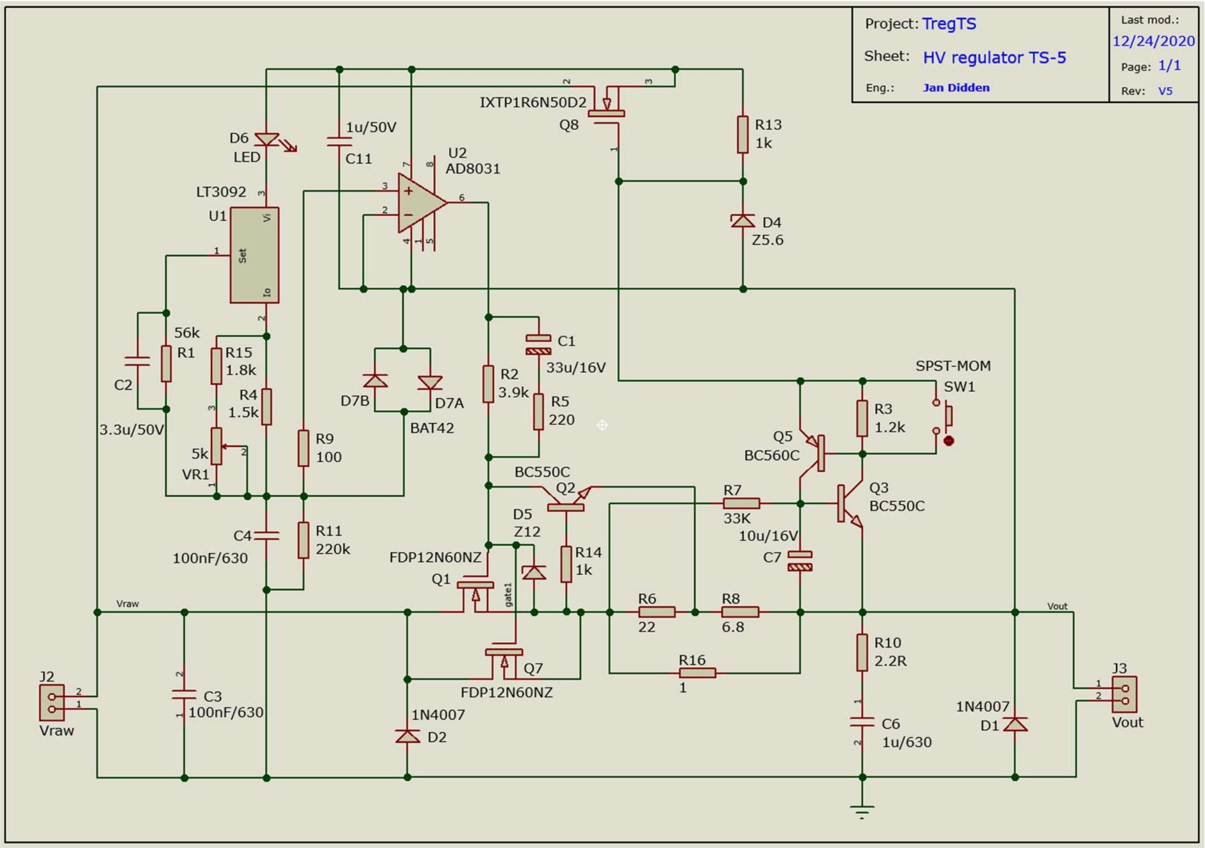


Fig 1 – the Full Monte

U2 has two inputs. The non-inverting input (‘+’ in the triangle) is connected to a reference voltage. We will look at that later, but for now assume it is a rock-stable voltage representing the requested Vout. The other U2 input (‘-‘ in the triangle), the inverting input, is connected to Vout. It all falls into place now: whenever Vout gets lower than the reference, U2’s output goes up (remember, Vout is connected to the *inverting* input), and that raises the gate voltage of Q1 through R2/R5/C1, opening up Q1 further to restore Vout to the reference setting. The inverse happens when Vout starts to increase above the reference voltage.

Reference voltage. You realize by now that the reference voltage (let’s call it Vref from now on) is of utmost importance: U2 will faithfully try to replicate the reference voltage at Vout. Any noise or ripple on Vref will appear at Vout. Vref starts with U1, an LT3092 which is a high performance programmable current source. The idea is that when you have a good stable noise free current into a stable resistor, you got yourself a good, stable, low noise reference voltage. U1’s current is programmed with and multiplied by R4/R15/VR1. This low noise current feeds into R11 and thus generates the reference voltage across R11, which is then fed to U2’s non-inverting input through R9. So, by selecting R11, you select the Vout value. VR1 offers the possibility to fine-tune Vout at about +/10% around the nominal voltage.

Current limiting and protection. So now we have a basic working regulator. But we also wanted a means to limit the output current in case of a calamity or downright shorts. That *does* happen, is bad enough in itself and the last thing you'd need is a blown regulator. Q2 takes care of that, and now we need that R6 we disregarded before. The load current flows through R16 and the voltage that this generates over R16 divides itself between R6 and R8, and when the voltage across R6 gets to about 0.6V, Q2 starts to conduct and syphons off the voltage that U2 sends to the gate of Q1. Eventually, Q2 wins, and the output current cannot increase anymore, and consequently Vout drops.

But we are not home free yet. Suppose you have a 500V regulator with a hard short, the current is limited at say 200mA, and Vout has dropped to zero. So that poor Q1 sees the full 500V+ Vraw across its body at 200mA and that means *a lot* of watts dissipation. Q1 will only last a very short time so unless we do something about it, we still end up with a blown regulator! Enter the circuitry around Q3 and Q5. This is a nifty circuit called a discrete triac[2]. The same load current that causes Q2 to limit the drive to Q1 also causes C7 to charge and eventually, after a few 100 milliseconds, ignite Q3. Q3 in turn ignites Q5, and the end result is that the supply voltage for both the current source U1 and opamp U2 collapses (we will discuss this supply later). So the sequence of events is that Q2 limits the current to the maximum allowed value, and if that persists for more than a few 100 milliseconds, Q3/Q5 remove the drive voltage altogether and the regulator is effectively shut down. If you know how to remove the overload or short, but don't want to recycle power on, you can press the little pushbutton SW1. This will interrupt the clamp down by Q3/Q5 and the regulator will operate normally again (assuming the short has been removed).

Auxiliary supply. Both the current source U1 and opamp U2 need a supply to operate. Because they operate at levels at or above Vout, this auxiliary supply must also be higher than Vout. Fortunately, that is available: to work, a regulator always needs an input voltage (Vraw) that is somewhat higher than the output voltage (Vout). We can use Vraw to develop the auxiliary supply for U1 and U2. For that we enlist the help of Q8, another high-voltage MOSFET. Let us assume that at switch-on this MOSFET starts to conduct current. This current flows through R13, and the voltage developed across R13 forms the Vgs of Q8. When that voltage reaches the value to maintain the current that generates it, the current is stabilized at that value. With the Q8 device specified and R13 being 1k, the current where Q8 settles at is about 3mA. This current also flows through D4, a 5.6V Zener, and then eventually flows to ground through the load. Thus, the source voltage of Q8 settles at around 8V above Vout, and this is the auxiliary supply for U1 and U2.

---

[2] There are small TO-92 type triacs but for this application I couldn't find one that was sensitive enough, hence the discrete one.

Floobydust. There are some additional parts for protection, stability, that sort of thing. C2/C4 further decouple the reference voltage for low noise. D1, D2 protect the regulator in case the input is removed with the output caps still charged, or vice versa. Similarly, D7a, D7b protect the control circuitry from such events. R10, C6 keep the regulator stable no matter what the load. R2 provides a highish DC path from the opamp to the gate of the pass device, so that the current limit circuitry can override it, while R5/C1 provide a low impedance path to be able to react quickly to transient load current changes.

Important: use *either* Q1 *or* Q7, but *not both*! They are in the schematic because there are two positions on the PCB, one for Q1 for use with the on-board heat sink specified in the BoM, or Q7 at the board edge if you want to use an off-board heatsink.

Stuffing the PCB

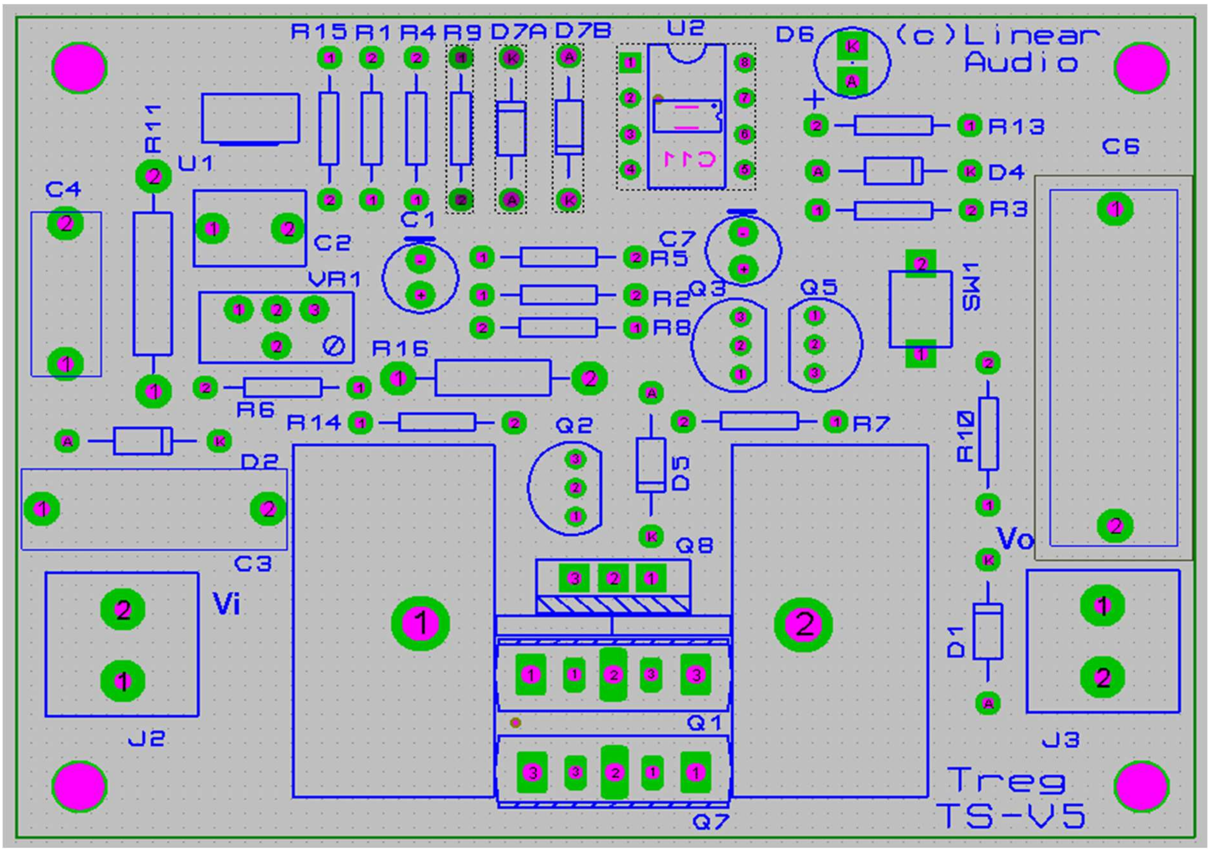
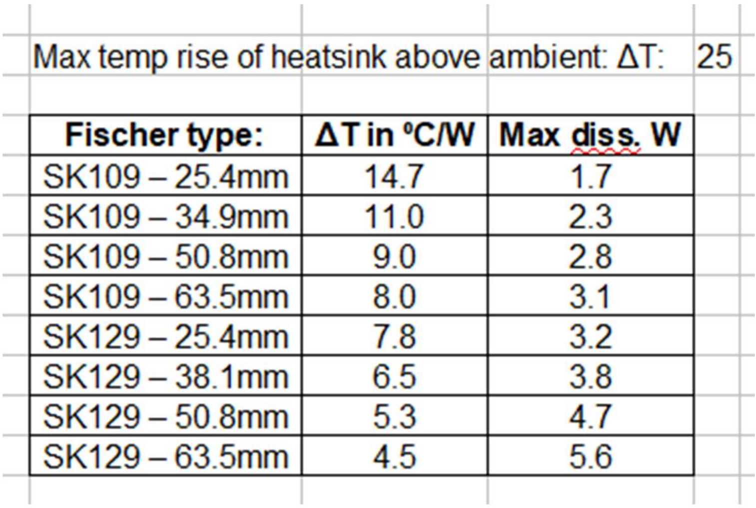


Fig 2 – PCB stuffing guide

Fig 2 shows the PCB stuffing guide. The SMD part U1 and SW1 are already soldered to the PCB. There is also an SMD cap at the back side of the PCB, beneath the opamp for decoupling, which you need to solder. It is huge as SMD goes so it should not be a problem. Next do all small and low-height parts, proceeding to the small-signal transistors, the electrolytics, the connectors and the high voltage film caps C3, C4, C6. Note that the *negative* pin for the electrolytics is indicated with a bar.

Q8 is mounted on the on-board heatsink on the side of the board, while Q1 finds a place on the outside board edge side of that heatsink. Table 1 gives some info on the height of the on-board heatsink related to the expected dissipation, assuming it should not rise more than 25° above ambient. Of course, for high dissipation, use Q7 *instead of* Q1 and mount it to an off-board heatsink. In any case, both the tab of Q8 and Q1 are connected to the same voltage so you can mount both on the heatsink without any isolation material, but then of course the heatsink carries the full output voltage – be careful!



Max temp rise of heatsink above ambient: ΔT: 25

Fischer type:	ΔT in °C/W	Max diss. W
SK109 – 25.4mm	14.7	1.7
SK109 – 34.9mm	11.0	2.3
SK109 – 50.8mm	9.0	2.8
SK109 – 63.5mm	8.0	3.1
SK129 – 25.4mm	7.8	3.2
SK129 – 38.1mm	6.5	3.8
SK129 – 50.8mm	5.3	4.7
SK129 – 63.5mm	4.5	5.6

Table 1 – heatsink selection guide

Bill of Materials

The BOM is listed separately on the website. For the critical parts, the Mouser part numbers are given. U1 and SW1 are pre-soldered on the PCB.

How to set the output voltage

Vout can be set with a single resistor, R11 in the circuit diagram. The reference current generated by U1 is approximately 580uA. So, for every kΩ R11 has, 0.58V will be generated across R11. Or, conversely, 58V per 100kΩ of R11. So, if you want for example 275V output, your R11 will need to be 275/0.58 kΩ which is 474kΩ nominal. You can adjust the final output with trimmer VR1 so for this 275V get a 470kΩ resistor and trim the final value.

Make sure you get an R11 resistor that can withstand the output voltage plus a safety factor. Distributors like Mouser have a wide selection for such parts.

Also remember that the maximum Vraw input voltage is 500V[3] so the Vout is probably limited to 480V depending on the input ripple voltage.

How to set the current limit

A single resistor, R16, needs to be selected to set the current limit. Current limiting occurs when the voltage across R16 gets to about 0.8V. So, for example, if you want a current limit of 180mA, your R6 will be 0.8/0.180 = 3.3Ω. Luckily, this is a standard value. If not, select the next higher value for a slightly lower current limit.

It is a good idea to use a larger resistor because of the current it may have to handle in case of a short, although the power dissipation is not high; at 400mA and 0.8V is it still only a quarter of a Watt. There’s ample space on the board for a 1W metal film resistor.

Remember: for reliable short-circuit protection, don't go above 400mA limit, better stay below it.

Have fun and happy soldering!

---

[3] There is an option to extend the absolute max input voltage to 600V by replacing Q8 with an ITXP01N100D. Not readily available but sometimes carried by distributors.